

Planets Rapidly Create Holes in Young Circumstellar Discs

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ABSTRACT

Recent spectral observations by the Spitzer Space Telescope (SST) reveal that some discs around young ($\sim \text{few} \times 10^6$ yr old) stars have remarkably sharp transitions to a low density inner region in which much of the material has been cleared away. It has been recognized that the most plausible mechanism for the sharp transition at a specific radius is the gravitational influence of a massive planet. This raises the question of whether the planet can also account for the hole extending all the way to the star. Using high resolution numerical simulations, we show that Jupiter-mass planets drive spiral waves which create holes on time scales ~ 10 times shorter than viscous or planet migration times. We find that the theory of spiral-wave driven accretion in viscous flows by Takeuchi et al. (1996) can be used to provide a consistent interpretation of the simulations. In addition, although the hole surface densities are low, they are finite, allowing mass accretion toward the star. Our results therefore imply that massive planets can form extended, sharply bounded spectral holes which can still accommodate substantial mass accretion rates. The results also imply that holes are more likely than gaps for Jupiter mass planets around solar mass stars.

1. Introduction

The discovery of extrasolar planets some 10 years ago has led to a renaissance in our understanding of the formation and evolution of planetary systems (Marcy & Butler 1998). Planets form accretion disks that surround and feed mass onto young stars, but there is significant gravitational feedback between the planets and their parent disks (Lin 2003). This produces a variety of disk architectures that often differ from our own solar system. Understanding planet-disk interactions is essential for understanding planetary positions, observational signatures for exo-planets, and the time scales that planet formation models must accommodate.

Despite significant theoretical progress (Lin 2003), key questions remain. The time scale for planet formation, τ_f , remains uncertain. Gas giant planets might form rapidly ($\tau_f \sim 1000$

y) through gravitational instability (Boss 2005), or slowly through core accretion (Lissauer 2001) where agglomeration of dust grains creates a rocky core that accretes surrounding gas. Core accretion has been estimated to take ~ 10 My, although recent arguments (Rafikov 2004; Matsumura & Pudritz 2005) lowering this to \sim Myr may be required by SST observations.

SST has provided a rapidly growing database of high resolution IR spectral observations of young disk-star systems. From the deficit of emission at wavelengths characteristic of the disk inner regions, the observations imply that some systems have mass-depleted inner disks: Surrounding the star CoKuTau/4 is a disk with a 9 AU spectral hole bounded by a very sharp outer edge, strongly indicative of the influence of a planet. Within 9 AU, the hole seems to require a density to be $\leq 10^{-4}$ times that which would otherwise be present if the disk inferred at 9AU were extended via standard models all the way to the star (D’Alessio et al. 2005). Such holes extend are beyond the scale for which a magnetic field would be important (Königl 1991) and the sharpness is unlikely to be explained by a radiation pressure or a wind (D’Alessio et al. 2005). While the presence of a planet is currently the most plausible explanation for the sharp edge and hole, the young age (D’Alessio et al. 2005) of the system, ≤ 2 My presents challenges for planet formation models (Quillen et al. 2004). SST observations of other systems reveal direct evidence for accretion in systems with and without spectral holes (Muzerolle et al., 2005, N. Calvet & D. Watson, personal communication)

Here we show, via direct numerical simulations, that Jupiter mass planets orbiting a solar mass star clear out inner holes all the way to the star on a time scale faster than the viscous or planet migration time scales. We identify this fast accretion with enhanced angular momentum transport by spiral waves induced by the planet and we find that a specific limit of the general theory of Takeuchi et al. (1996) of spiral wave angular momentum transport in turbulent disks offers a consistent explanation of our results.

We emphasize that in our calculations, the planet is embeded in an already turbulent disk with an α -viscosity Shakura & Sunyaev (1973). Our approach therefore differs from e.g Spruit (1987), for which the disk has no means of angular momentum transport other than a dissipation of spiral waves themselves. For the latter, Larson (1990) showed that, in the absence of turbulent viscous damping, waves will become weak shocks, which can provide a modest effective viscosity Savonije et al. (1994). This mechanism was shown by Spruit (1987) to be effective for hot disks and has been called ”wave accretion” (Larson 1990). It was originally presented, in the case of white dwarf binaries, as a possible explanation for the observed optical periodicities in Murray et al. (1999). While our work here does appeal to the impact of spiral waves in the transport of angular momentum, it is important that for

us these waves act in addition to the baseline disk turbulence. In the case considered herein, the pre-existing turbulent viscosity keeps the waves linear, preventing steepening into shocks and thereby allowing transport over farther distances from the wave launch point. This increases the effective angular momentum transport from the case where weak shocks form as long as the initial viscosity is not too large.

In addition to showing that our results are consistent with the theory of Takeuchi et al. 1996, we use the results to account for the recent spectral holes observed in young YSO system such CoKuTau 4 (D’Alessio et al. 2005).

In section 2 we discuss our numerical calculations of the surface density and accretion rate evolution. We discuss the results, interpretation, and implications in section 3 and conclude in section 4.

2. Surface Density and Accretion Rate Evolution

To determine whether planets can produce sharp extended spectral holes and to calculate the associated mass accretion rates, we have carried out a series of 2-D simulations of planets opening up disk gaps which then evolve into holes as material drains onto the star. While there have been previous numerical simulations of gap formation (Bryden et al. 1999; Kley 1999; Nelson et al. 2000; Varnière et al. 2004), our work differs in that we have followed the disk accretion significantly longer, capturing the inner disk clearing all the way to the star.

2.1. Numerical Simulation Set-up

We use a code which eliminates the azimuthal velocity from the computation of the Courant-Friedrich-Lévy condition. (Masset 2000, 2002; Masset & Papaloizou 2003). This speeds up the computation and facilitates studying the long term disk evolution. Our simulations begin with a viscosity parameter $\alpha = \nu/ch = 0.00625$, where ν is the viscosity and $c(r)$ is the local sound speed. The disk height-to-radius ratio $h/r = 0.04$, independent of radius. This corresponds to a Reynolds number $\mathcal{R} \equiv \Omega r^2/\nu = \Omega r^2/(\alpha ch) = (1/\alpha)(r/h)^2 = 10^5$, where $\Omega(r)$ is the Keplerian speed. We performed simulations with 100×300 grid cells and 150×450 grid cells to test for convergence.

In the absence of a planet, accretion at any radius occurs at the viscous time $t_\nu = \mathcal{R}/\Omega(r)$ ($\sim 1.6 \times 10^4$ yr at 1AU). Here we compare this to the case when a planet is present. We ran simulations for a variety of planet masses $M_p = 0.001, 0.002$, and $0.005 M_\odot$, orbital radii $r_p = 1, 5$ and 7 AU, and initial surface density profiles $\Sigma \propto r^{-q}$ with $q = 0, 1$. The two values

for q exhibit similar results. We focus on the $q = 1$ case herein. The planet was always initially set onto a circular orbit and was free to migrate via angular momentum exchange with the disk. The planet was allowed to accrete gas within its Roche Lobe. Self-gravity is unimportant for our disks.

2.2. Quantitative Results

Fig. 1 shows $\Sigma(r)$ at five different times for a case in which $r_p = 1$ AU and $M_p = 0.001 M_\odot = 1 M_J$. As seen at $t = 1000$, the surface density in the inner regions first increases as matter is pushed toward the star and the gap opens, but an inner hole forms subsequently as material is lost to the star. The gap near 1AU forms in less than 1000 orbits and a hole cleared all the way to the star (i.e. $\Sigma(r_* \leq r \leq r_p)$ drops by factor ≥ 10 for all $r_* \leq r \leq r_p$, where r_* is the radius of the star) clears by ~ 2000 orbits which is $\sim 1/10$ the viscous time at $r = r_p$. By 6000 orbits, the surface density has dropped by a nearly a factor of 10^{-5} at 1AU and by 10^{-3} at 0.4AU.

Fig. 2 shows the time evolution of disk mass $M_r(t)$ within $r_* \leq r \leq r_p$. The cases shown have $M_p = 0.001 M_\odot = 1 M_J$ and $M_p = 0.002 M_\odot = 2 M_J$ and $r_p = 1$ AU. From $900 < t < 2000$ orbits, $M_r(t)$ rapidly depletes by a factor of 25. This is ~ 0.1 viscous accretion times at $r = r_p$ and consistent with the rapid gap formation, followed by a slower, but still faster-than-viscous depletion at smaller r . The upper, almost straight, line in Fig. 2 represents the mass evolution in the case with NO planet in a disk limited to a 1 AU size, for comparison with the much faster time evolution of the surface density when the planet is present. The distinction shows that the enhanced surface density evolution is not a boundary condition effect.

Fig. 3 shows the accretion rate onto to the star, $\dot{M}(t)$, for the two mass cases. Measurements of SEDs for disks are sensitive to dust only, and the gas density is inferred from assuming a gas-to-dust density ratio (D'Alessio et al. 2005). Direct measure of ρ_g requires detection of molecular lines such as those from CO, which is difficult. For a given α , measuring \dot{M} provides an alternative measure of ρ_g . Observations of proto-planetary disks with SEDs showing holes often indicate accretion rates $\dot{M} \sim 10^{-9} M_\odot/\text{yr}$. (Muzerolle et al. 2005). Despite the spectral holes, this rate is still large, of order 10% of the rates typical for similar disks without an inner hole (called Class II objects). The accretion rate at any given time depends on the initial disk mass, which can vary between systems, so an important quantity to extract from simulations is the ratio of the initial \dot{M} to that after the spectral hole is present. In our simulations, the initial parameters give $\dot{M}(t = 0) \simeq 4 \times 10^{-8} M_\odot/y$. Focusing on the $M_p = 1M_J$ case of Fig. 3, \dot{M} rises to nearly $\dot{M} = 100\dot{M}_a(t = 0)$ at $t = 1900y$, and

subsequently drops to $\dot{M} \sim 0.05\dot{M}_a(t=0)$ at $t = 6000$ y after which it continues to decay. Figs. 1-3 thus demonstrate both (1) rapid hole formation and (2) substantial accretion rates even after a hole of with a 10^{-3} deficit in surface density has formed. Note also that the absence of significant planet migration on the hole clearing time suggests that spectral holes likely accompany massive planets.

In fig 4 we compare the SED at two different times during the hole formation with the planet-free case. The figure shows the planet’s effect on the spectra as early as 3000 orbits (on the left). The effect grows stronger with time until a spectral hole forms.

3. Interpretation and Implications

3.1. The role of spiral waves in clearing the gap and hole

The faster-than-viscous rapid hole formation exhibited in Figs.1-3 is due to outward angular momentum transport at $r < r_p$ from spiral waves driven off of resonances between the orbital motion of the planet and disk material (Goldreich & Tremaine 1980; Takeuchi et al. 1996). As mentioned in the introduction, our approach is different from that of Spruit (1987); Larson (1990) and Murray et al. (1999), as we take an already viscous disk. Savonije et al. (1994) showed that, in the absence of viscous damping, weak shocks produced by the spiral waves, provide an effective viscosity $\alpha \sim (c/r\Omega)^3$. We therefore proceed to analyze our results in the context of Takeuchi et al. (1996) who considered spiral wave induced angular momentum transport in which turbulent viscosity damps the waves sufficiently to sustain keep them linear, before they steepen weak shocks. Since angular momentum is transported only over the damping length, a finite viscosity allows waves to transport angular momentum over a large distance. If the initial viscosity were too high, then the waves would have no effect. Our viscosity and planet-to-star mass ratio satisfy the condition in Takeuchi et al. 1996 for enhanced transport to be expected.

The time evolution of the surface density $\Sigma(r)$ satisfies

$$\frac{\partial \Sigma}{\partial t} = \frac{3}{r} \frac{\partial}{\partial r} \left[r^{1/2} \frac{\partial}{\partial r} (\nu \Sigma r^{1/2}) - \frac{r^{1/2}}{2\pi(GM_\star)^{1/2}} T \right], \quad (1)$$

where the first term on the right is due to viscous accretion and the second is due to the action of spiral waves. The total torque per unit length produced by the planet on the disk is given by $T = \sum_m T_m \propto \pm M_p^2 \Sigma r^4 / (M_\star (r - r_p)^4)$, where the subscript m refers to the m-th orbital Lindblad resonance (Goldreich & Tremaine 1980; Takeuchi et al. 1996). Interior to the planet, spiral waves enhance the outward angular momentum transport from a purely

viscous disk. They transport angular momentum out to a distance to which the waves damp. A formula for the damping length l is given by Takeuchi et al. (1996) as

$$\left[\left(\zeta + \left(\frac{4}{3} + \frac{\kappa^2}{m^2(\Omega - \Omega_p)^2} \right) \right) \nu \frac{m(\Omega_p - \Omega)}{c^2} kl \right]_{r_L - l} \simeq 1, \quad (2)$$

where $\kappa \simeq \Omega$ is the epicyclic frequency, ν is the shear viscosity, ζ is the bulk viscosity, k is radial wavenumber of the mode, and m is the azimuthal wave number, and $r = r_L - l$ is the radius at which quantities are to be evaluated, where r_L represents the location of the Lindblad resonance at which the wave of mode m is launched.

Near $r = r_p$, the angular momentum transport is initially dominated by the second term on the right of Eq. (1) from waves launched at the $m \sim r/h \simeq 25$ resonance (Takeuchi et al. 1996). Assuming that the initial gap corresponds to the damping length of these large m waves, Takeuchi et al. (1996) obtain for the gap width (2)

$$\Delta r \sim l \sim r_p (c/r\Omega)_p \alpha^{-2/5} \sim (r_p/3)(h/r/0.04)(\alpha/0.006)^{-2/5}, \quad (3)$$

where α is specifically used to replace the combination of $\zeta + 4\nu/3$. The $m \sim r/h$ waves produce the gap seen near $r = r_p$ at 1000 orbits in Fig 1.

Although the large m linear waves that form the initial gap transport angular momentum faster than small m waves, the latter damp over a shorter distance. Once large m waves clear out a gap, the decrease in surface density at their launch location reduces their subsequent contribution to the global angular momentum transport, and the influence of the higher density inner regions takes over. We now argue that the faster-than-viscous hole clearing by $t \sim 2000$ is consistent with low $m = 2$ waves launched from their Lindblad resonance at (e.g. Shu (1992)) $r_L = (1 - 1/m)^{2/3} \sim 0.63r_p$ dominating T . (We note that $m = 2$ are the lowest modes relevant for a Keplerian disk but $m = 1$ could be relevant for sub-Keplerian disks for which Ω differs significantly from κ .)

The damping length l in the limit of low m waves is not explicitly estimated in Takeuchi et al. (1996), but we can estimate it from the low m limit of (2). To do so, we assume (to be justified later) that the damping length l is large enough that $r_L - l \ll r_p$, so $\Omega(r_L - l) - \Omega_p \sim \Omega(r_L - l)$. Then (2) becomes

$$(\zeta + (4/3 + 1/m^2)\nu)(mkl\Omega/c^2) \simeq 1. \quad (4)$$

We use the approximation $\zeta + (4/3 + 1/m^2)\nu \sim \zeta + 4/3\nu \sim \alpha ch$. so that (4) becomes

$$l = 1/(\alpha km), \quad (5)$$

where (Takeuchi et al. (1996))

$$k = \left[\frac{m^2(\Omega - \Omega_p)^2 - \kappa^2}{c^2} \right]^{1/2} \sim \frac{(m^2 - 1)^{1/2}}{h(r_L - l)} \sim \left(\frac{3^{1/2}}{0.63r_p - l} \right) \frac{r}{h}, \quad (6)$$

and the latter similarity follows for $r_L = 0.63r_p$ and $m = 2$. Using (6) in (5) then gives

$$l = 0.36r_p \frac{h}{r} \frac{1}{\alpha} \left(1 + \frac{0.5}{3^{1/2}} \frac{h}{r} \frac{1}{\alpha} \right)^{-1}. \quad (7)$$

If we take $\alpha = 0.006$ and $h/r = 0.04$ as per our simulations, then for $m = 2$, $l \sim 0.42r_p$, so that $r_L - l = 0.63r_p - l \sim 0.21r_p$. The viscous time at $r = 0.21r_p$ is $\frac{\mathcal{R}}{2\pi}(0.21)^{3/2}\text{yr} \sim 1530\text{yr}$. Fig. 1 shows that by 2000yr, $\Sigma(r)$ has decreased by at least a factor of 10 from its initial value for all radii. Were this purely the result of viscous evolution, we would see such clearing only for $r \leq 0.2r_p$. In short, the clearing at all radii out to r_p illustrates the initial influence of $m = r/h \sim 25$ spiral waves followed by the subsequent influence of $m = 2$ spiral waves.

We can define the hole formation time as the time scale at which the surface density at $r \leq 2r_p/3$ drops by factor of 10. We use this radius since, as discussed above, the gap opens from $r_p \geq r \geq r \sim 2r_p/3$. Thus the hole formation represents the remaining clearing inside $r \leq 2r_p/3$. The mass scaling for the hole clearing time scale can be estimated using $\tau_h \sim \frac{\Sigma}{\partial_t \Sigma}$ and the third term of Eq. (1). Measured in units of the planet's orbit period, the result is

$$\tau_h(2r_p/3)\Omega(r_p) \sim 0.1 \frac{\mathcal{R}}{2\pi} \left(\frac{M_*}{1M_\odot} \right)^{3/2} \left(\frac{M_p}{1M_J} \right)^{-2}, \quad (8)$$

where the numerical coefficient 0.1 comes from the simulations (e.g. Fig. 1) while the parameter scalings come from the theory. The result (8) is ~ 0.16 the viscous time at $r = 2r_p/3$ and 0.1 times the viscous time at $r = r_p$.

3.2. Implications for observing holes and gaps

Finally, we point out that for a planet to have any observable effect, it must form faster than the migration time scale at its formation location. In our planet-disk simulations, we imposed a planet at $t = 0$, so the planet formation time scale is unspecified. However, a constraint emerges. If the planet growth time is long compared to the hole formation time scale, τ_h , then a spectral hole should always accompany the planet. If instead the planet formation time, $\tau_f < \tau_h$, then the fraction of systems with a planet but without a hole, would be $f \sim \frac{\tau_h(2r_p/3)}{\tau_{mig}}$, and τ_{mig} is the migration time at the planet's inferred location.

From the simulations, we find that $\tau_{mig}\Omega(r_p) \geq \mathcal{R}/2\pi$ (where the equality corresponds to $\Sigma(r, t = 0) \propto r^{-q}$ with $q \geq 0$) . Then, using (8) $f \sim 0.1 \left(\frac{M_*}{1M_\odot}\right)^{3/2} \left(\frac{M_p}{1M_J}\right)^{-2}$.

Our key result, that massive planets rapidly form spectral holes in disks, thus implies: (1) For planet formation on a time scale $\tau_f > \tau_h$, all disks with a massive planet will have a sharply bounded hole from outer radius $r_{out} = r_p$ to inner radius $r_{in} = r_*$. (2) For $\tau_f < \tau_h$, a fraction f of disks with a massive planet would show a sharply bounded gap from $r_{out} > r_p$ to $r_{in} > r_*$. (3) However, since f is small for massive planets. Therefore, disks which appear to show gaps but not holes (Marsh & Mahoney 1992, 1993) are best explained either by planets with low enough mass to make τ_h as long as the viscous time (in which case only the early gap formation is observed), or by spectral features from dust and inclination effects without a planet.

4. Conclusion

We find that a massive planet embedded in a protoplanetary accretion disk can produce a low surface density hole faster than can be accounted for by purely viscous evolution. In particular, (1) after less than 1000 orbits a very low surface density gap forms that extends approximately 1/3 the distance to the star. (2) By about 2000 orbits, a low surface density hole, with a factor of ≥ 10 density depletion extending all the way from the planet orbital radius to the stellar surface appears on a time scale ~ 0.16 of the viscous evolution time calculated at $r = 2r_p/3$.

The gap and hole are consistently interpreted to be the result of the enhanced angular momentum transport and accretion induced by spiral waves (Goldreich & Tremaine 1980; Artymowicz & Lubow 1994; Takeuchi et al. 1996). We find that the gap can be explained by the launching and damping of $m = r/h \sim 25$ waves and the faster-than-viscous hole formation is consistent with launching and damping of $m = 2$ waves. Our results are consistent with previous studies of gap formation and the theory of Takeuchi et al. (1996) but we have followed the evolution of the disk long much longer than in previous simulations (Bryden et al. 1999; Kley 1999; Nelson et al. 2000; Varnière et al. 2004) and we are able to see the hole clear all the way to the star.

Our results imply that spectral holes could be more common than spectral gaps when a sufficiently massive planet is present inside a disk. We also emphasize that the use of the term “spectral hole” is important because even though the holes have a reduced density for all $r_* < r < r_p$, they need not be fully evacuated and substantial accretion rates can be maintained even after the hole forms.

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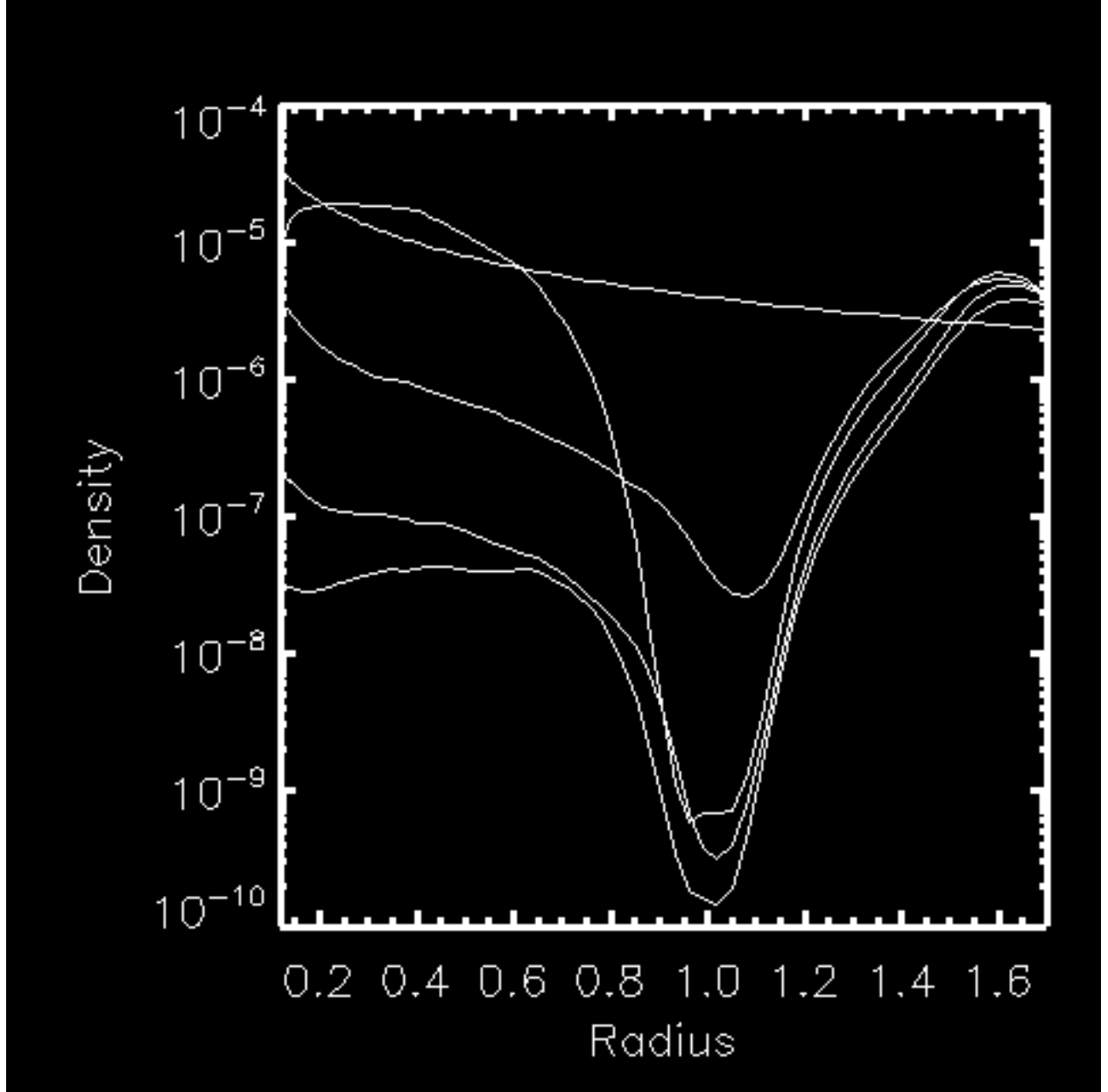


Fig. 1.— Evolution of the density in the inner region of the disk. There is a $1 M_J$ planet at 1AU. The different curves (identified from the top down at the inner edge) are 0, 1000, 2000, 4000, and 6000 orbital times at 1AU.

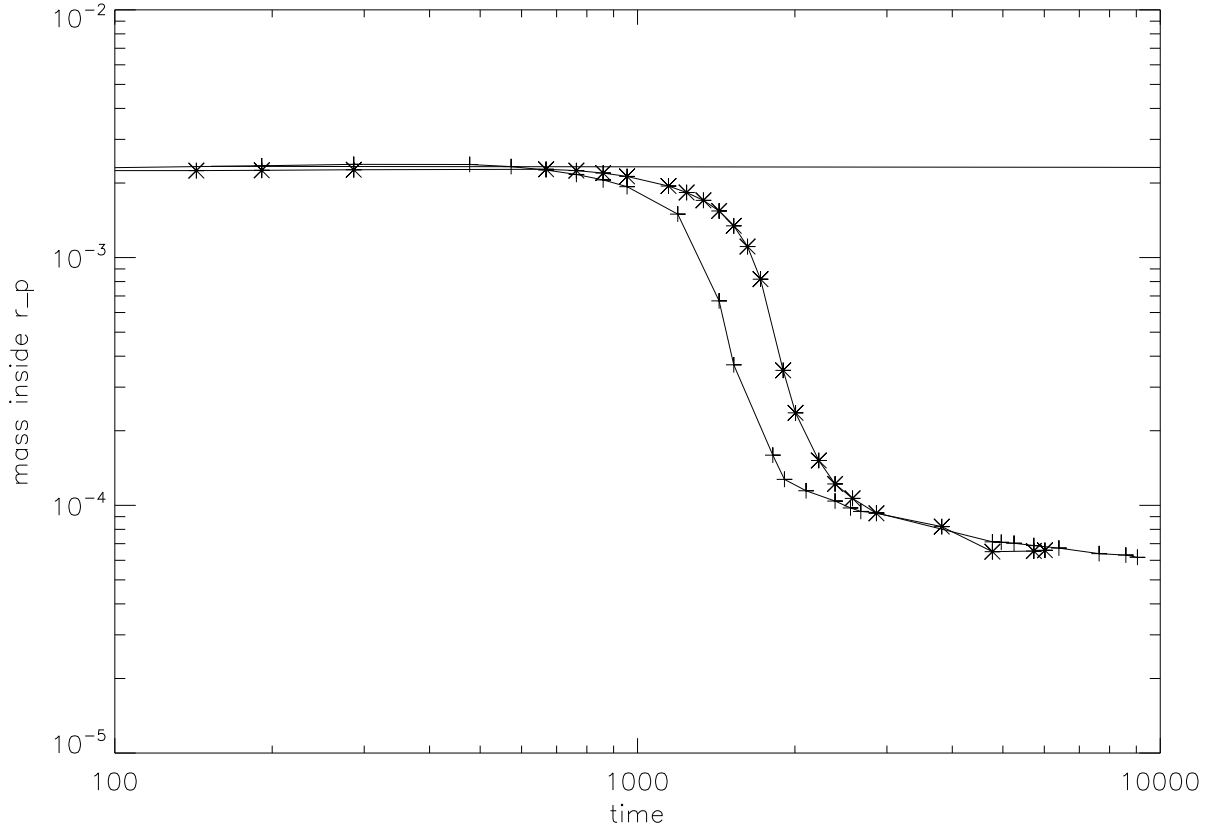


Fig. 2.— Evolution of the mass interior to the planet as a function of time for a planet at 1AU. the "*" represents a $1 M_J$ planet and the "+" a $2 M_J$ planet. The almost straight line is the same plot in the case of no planet in the system but a disk size limited to 1AU.

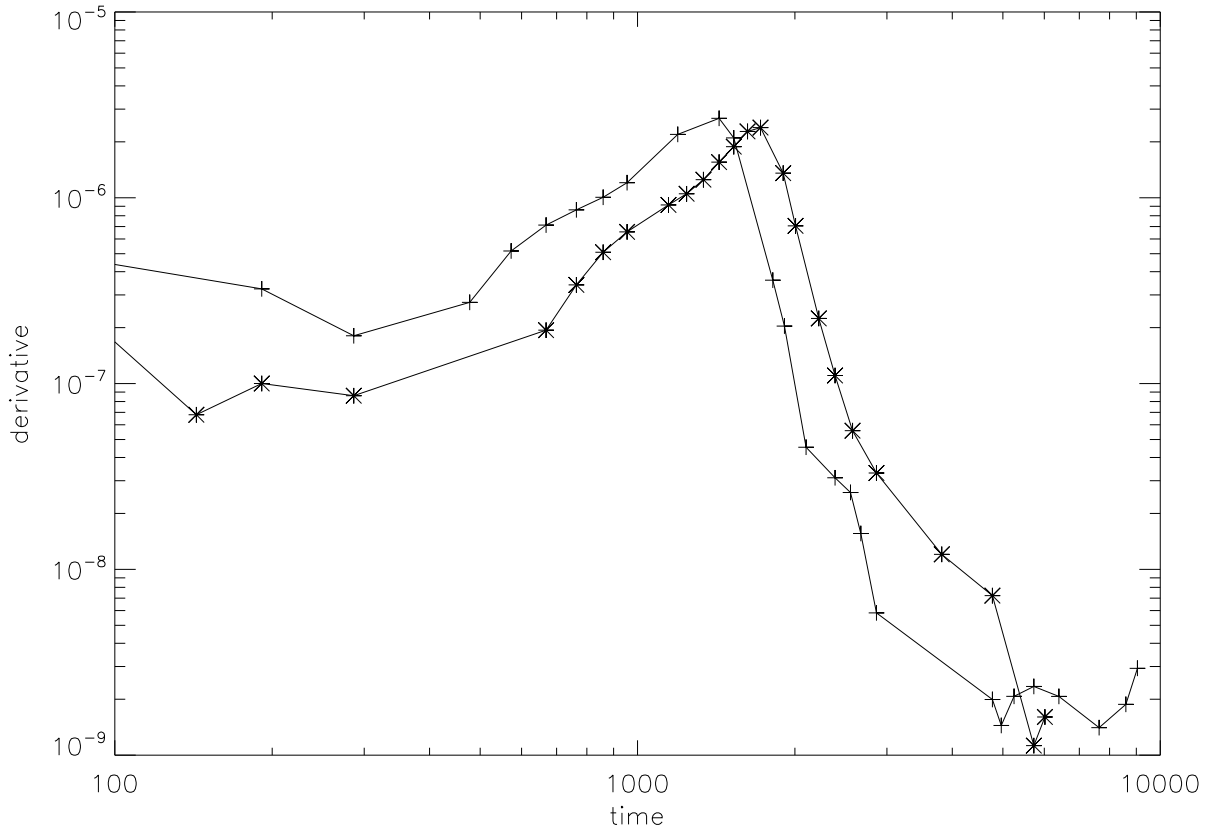


Fig. 3.— Evolution of the mass accretion rate as function of time for a planet at 1AU. the “*” represents a 1 M_J planet and the “+” a 2 M_J planet.

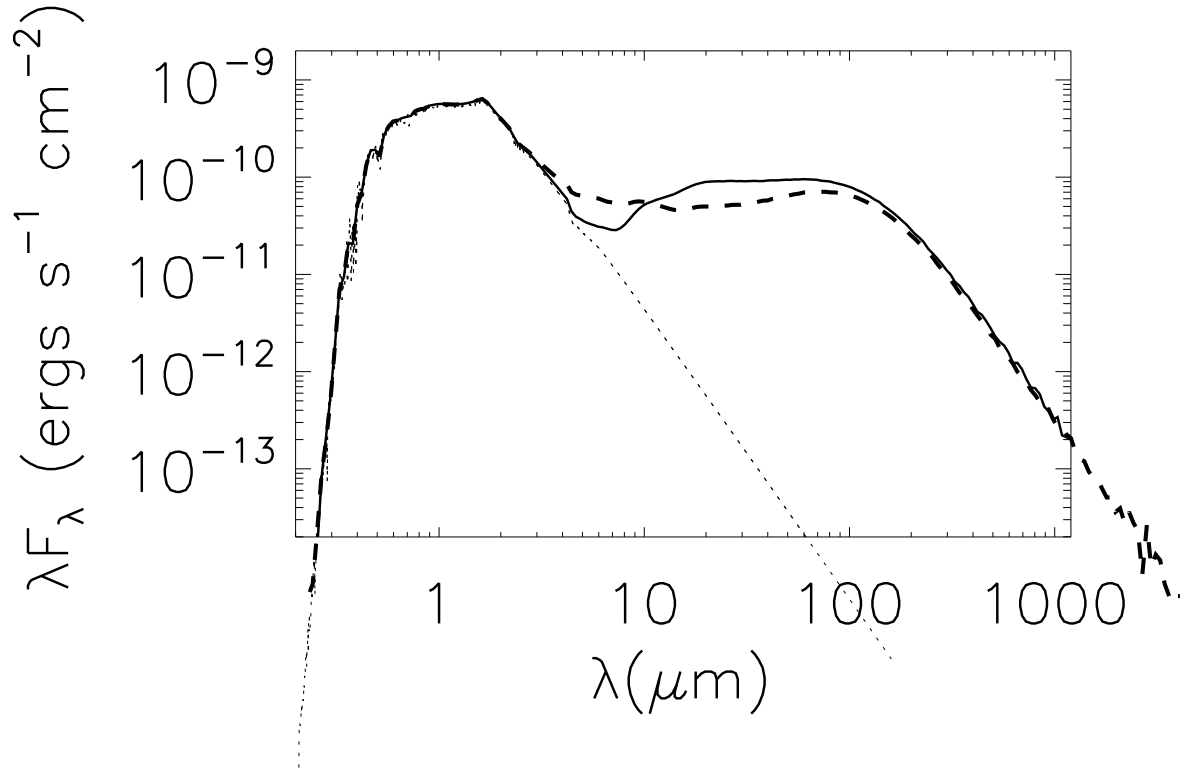


Fig. 4.— Spectral Energy Distribution (SED) after 10000 orbits, compared with the no-planet case. We see the creation of a spectral hole.